Understanding Magnetic Flux Leakage (MFL) Signals from Mechanical Damage in Pipelines

2nd QUARTERLY PUBLIC REPORT

Period: July through September 2005

Background

The objective of this project is to understand the origin of Magnetic Flux Leakage (MFL) signals from dents, the ultimate goal being to accurately characterize dents from MFL field inspection data. MFL dent signals arise from both the dent geometry as well as the residual stresses surrounding the dent. In this project, experimental and finite element modelling techniques are used to separate and understand both stress and geometry contributions to the MFL signals.

Earlier work (pre-2005) by the Queen's University Applied Magnetics Group involved examination of MFL signals from circular dents. The present US DOT PHMSA contract extends this study to include oval or "elongated" dents – specifically dents having a 2:1 length to width aspect ratio.

In the first quarter of the contract an oval denting tool was designed and constructed for use in the experimental part of the study. On the modeling side, stress Finite Element Analysis (FEA) modeling was conducted for simulated 2:1 aspect ratio elongated in the axial direction dents. In addition, magnetic FEA modeling was begun which utilized the stress FEA modeling results.

Summary of Progress this Quarter

In the second quarter of this contract work has continued on both experimental and modeling fronts. The subtasks for the second quarter have been completed satisfactorily and according to schedule. Experimentally the following subtask was completed:

- Subtask 1.4 – Observed experimental MFL patterns around axially-oriented oval dents

The corresponding magnetic FEA modeling work (for direct comparison with the experimental study) was also completed:

- Subtask 1.3 – Modeled MFL patterns around axially-oriented oval dents.

Finally, one of the later tasks will involve modeling and experimentally examining MFL signal around dents containing corrosion pits. In this quarter stress modeling was done to determine stress patterns around such dents:

- Subtask 2.1 – Modeled stress pattern around dents with corrosion.

A summary of work conducted on each subtask, including experimental results, is given in the Results section below.

ELECTRICORE
POWERING THE FUTURE

Contact

Ian Wood

Program Manager

Electricore, Inc.

Office: 661-607-0261

Fax: 661-607-0264

ian@electricore.org

www.electricore.org

Results

<u>Item No. 7 - Subtask 1.4: Experimental observations of MFL patterns around axially-oriented oval dents</u>:

<u>Samples:</u> Steel plate samples of dimensions 260mm x150mm x 3mm thick were dented using a hydraulic press fitted with the 2:1 aspect ratio oval denting tool and die that was designed and constructed in Task 1.1. Dent depths ranged between 3mm and 7mm. The resulting dent size (length and width) in each sample varied depending on the dent depth, but was approximately 45mm x25mm. MFL scans were obtained for each sample using the methods described below. Under these conditions the MFL signal is generated both by the dent geometry as well as the residual stresses around the dent. After the initial MFL scans were complete the dented samples were heat treated at 500^{o}C for 2 hours to relieve most of the residual stresses associated with the denting process. The MFL scanning was then repeated, with this post-annealing MFL result mainly associated with the dent geometry.

<u>MFL scanning equipment:</u> A schematic diagram of our laboratory MFL detection system is shown in Figure 1. This shows the side view of an MFL circuit sitting on the dented sample (in cross section). The MFL circuit includes high strength Nd-Fe-B permanent magnets and steel pole pieces to couple the flux into the sample. The MFL magnet is configured to produce a sample flux density of 1.5T.

A Hall probe detector is attached to the arm of an XY plotter (not shown), and during an MFL measurement it scans over a 40mmx40mm area above the dented region at 1mm intervals. The diagram in Figure 1 shows the Hall probe travelling over the "bottomside" of a dented sample, and illustrates that the probe itself does not follow the local surface contour but rather remains parallel to the undented surface as it passes over the dent. This is consistent with MFL inspection scans in the field.

The Hall probe can be oriented to measure either the axial, radial or circumferential components of the leakage flux signal, and is connected though an amplifier to a PC-based data acquisition system. The results of the 40mm x 40 mm Hall probe scans are typically displayed as contour plots.

The bottomside scan configuration is similar to the type of MFL measurement made in a typical pipeline inspection scenario, since the inspection tool is inside the pipe. In the present study we have also conducted 'topside' MFL scans. These are done using the configuration shown in Figure 1 except that the sample is 'flipped' to scan over the other side. The topside scan would correspond to a scan of the outer pipe surface, something that is rarely done in practice. Despite this, the topside measurement is useful for comparison with bottomside results and aids in interpreting contour plots, therefore we have made both topside and bottomside measurement on all dented samples.

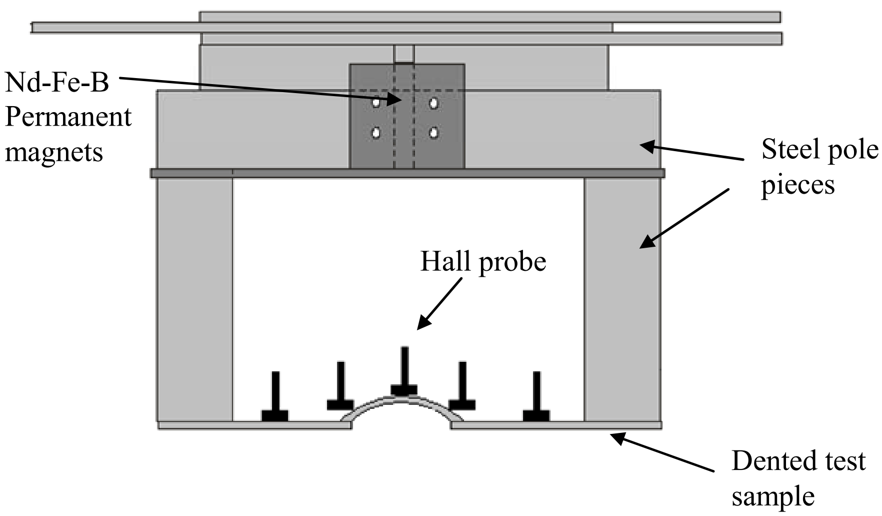

Figure 1: Side view of a typical laboratory MFL detection system. Only a single Hall probe is used and the diagram illustrates how it steps over the dent surface during a typical scan.

MFL scan results of 2:1 axially-oriented dents – before annealing Figure 2 shows typical MFL radial component, bottomside contour plots for the 2:1 aspect ratio dents before annealing, for increasing dent depths. A similar set of plots was obtained for the topside of the dent, and also after annealing for both bottom and topside. Earlier work on the circular dents indicated that the central features of the contour plot are geometry-related while the ‘shoulder’ peaks tend to be stress-related.

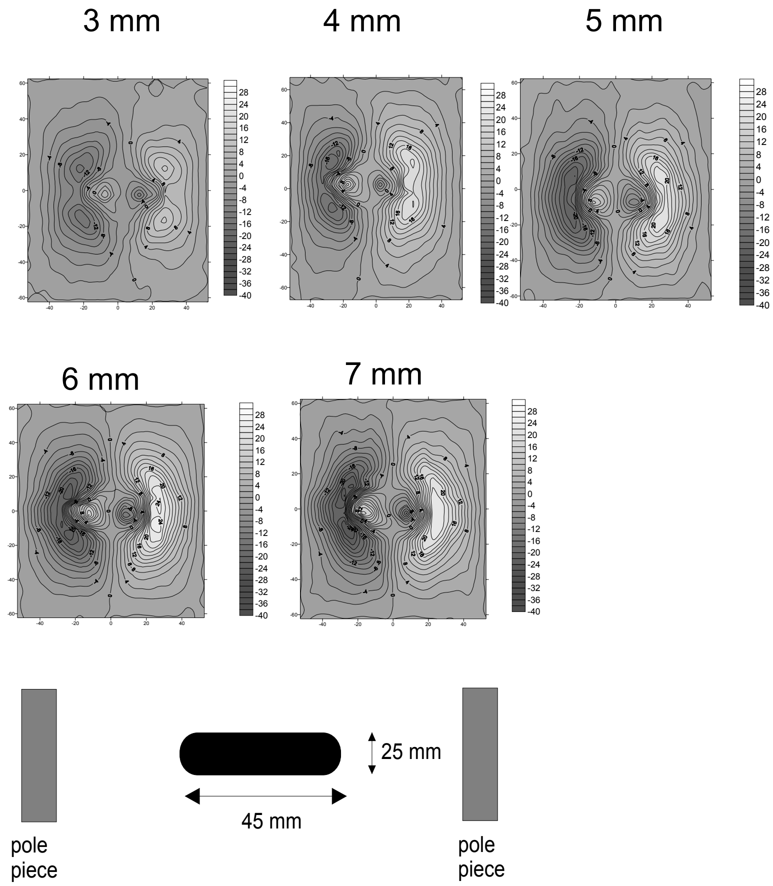

Figure 2 MFL radial component contour plots for the bottomside of the 2:1 dent, for dent depths of 3mm to 7mm. Results are for unannealed samples. The grey scale label on the side is in units of B_{radial} x 10^{-4}T. The schematic diagram at the bottom indicates the orientation of the dent relative to the magnet pole pieces and the contour plots.

Figure 3 shows some of the typical analysis performed on the contour plot MFL data. This graph shows the change in MFL peak-to-peak signal values with annealing for 4 different MFL peaks as a function of dent depth. Note here that the MFL_{pp} change for the central peaks (both bottomside and topside) is essentially negligible. This is expected since these peaks are largely geometry related. Conversely, the shoulder peak size changes significantly with annealing, consistent with the shoulder peaks being mainly associated with stress effects. The shoulder MFL_{pp} change also levels off above dent depths of 5mm indicating that stress effects become smaller at deeper dent depths.

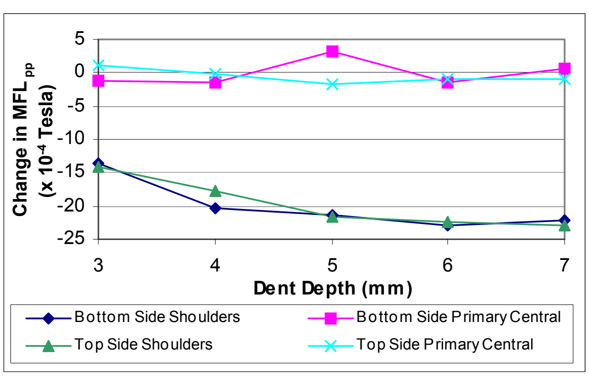

Figure 3: Change in MFL_{pp} signal with annealing for 4 different peaks seen in the MFL contour plots. The primary central peaks (both bottom and topside) change little with annealing, however the MFL_{pp} change for the shoulder peaks is significant.

Item No. 6 - Subtask 1.3: Modelling MFL patterns around axially oriented elongated dents

The previous quarterly report provided details of the stress FEA modelling used to obtain the residual stress distribution around the dent. This information was used to assign specific stress-related permeability functions to particular regions around the dent in the magnetic FEA model.

The magnetic FEA modelling of MFL signals from axially-oriented dents began in the previous quarter and continued into the second quarter as scheduled. Figure 4 shows the magnetic model constructed for the axially oriented elongated dent (only a quarter model is necessary because of symmetry). The modelled dent is 7mm deep. The segments in and around the dent indicate the regions where different permeabilities can be assigned. There are a total of 112 separate segments in this model. Note that the finite element mesh is much smaller than the size of these segments.

Examination of the stress FEA model (explained in 1st Quarterly Report) was used to determine the levels and directions of residual stress in the dent region. Magnetic permeability functions were assigned to the dent segments in Figure 4 according to the level of residual stress predicted by the stress FEA model. In Figure 4, for example, green segments have low (essentially zero) residual stresses; blue segments compressive stress, and purple tensile stress. Note also that the permeability function is a vector, therefore the stress direction is critical to the analysis and the model.

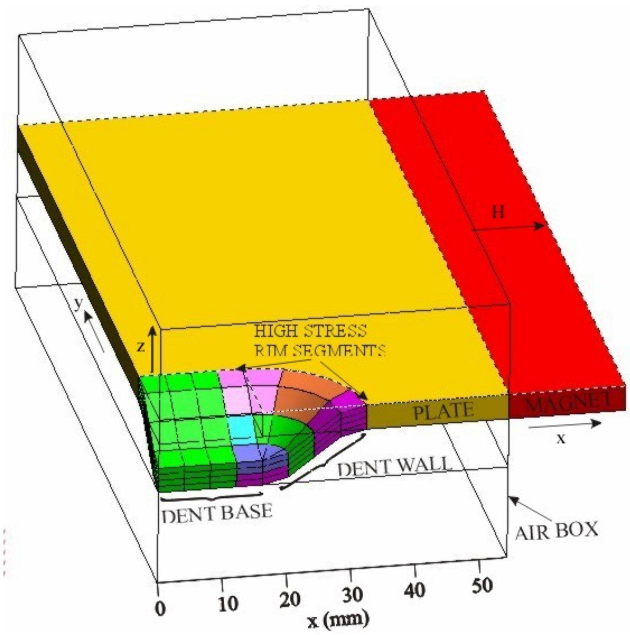

Figure 4: The magnetic FEA model for the axially elongated dent. The magnet region is shown in red. Only a quarter model is necessary due to symmetry. The dent region is divided into 112 segments. Each of these segments can be assigned a different magnetic permeability according to the residual stress predicted in that segment.

The advantage of the magnetic FEA model is that it is possible to 'isolate' either stress or geometry MFL signals. The geometry-only signal is created by assigning all of the segments in Figure 4 with the same isotropic permeability function that is present in the background plate. The geometry-only MFL (radial component) signal is shown in Figure 5.

The stress-only MFL (radial) signal is generated in two steps – 1) the geometry+stress result is obtained using the geometric model shown in Figure 4 which contains residual stress-altered permeability regions, and then 2) the geometry-only result (figure 5) is subtracted from this result. The stress-only MFL(radial) result is shown in Figure 6. It is worthwhile noting further that within the stress model each individual stress region can be turned "off" or "on" separately. This enables us to determine exactly which stresses are responsible for each peak.

Figure 7 shows the combined stress+geometry MFL radial component result containing all of the significant residual stress regions indicated by the stress FEA model. MFL axial and circumferential model results were also obtained but are not shown here. The result compares favorably with the experimental result for a 7mm deep dent shown in Figure 2, and further quantitative analysis is being conducted to compare the modeling and experimental work.

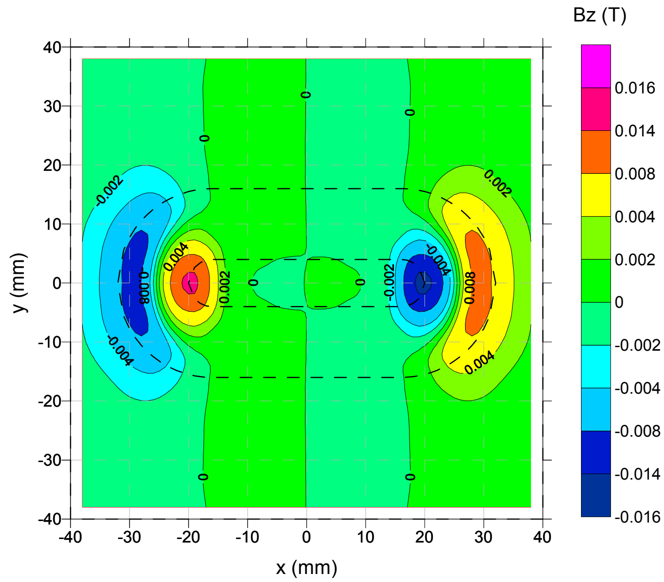

Figure 5: MFL radial component (z direction) geometry-only contour plot for the axially elongated dent model own in Figure 4. The dotted line on the plot indicates the dent perimeter.

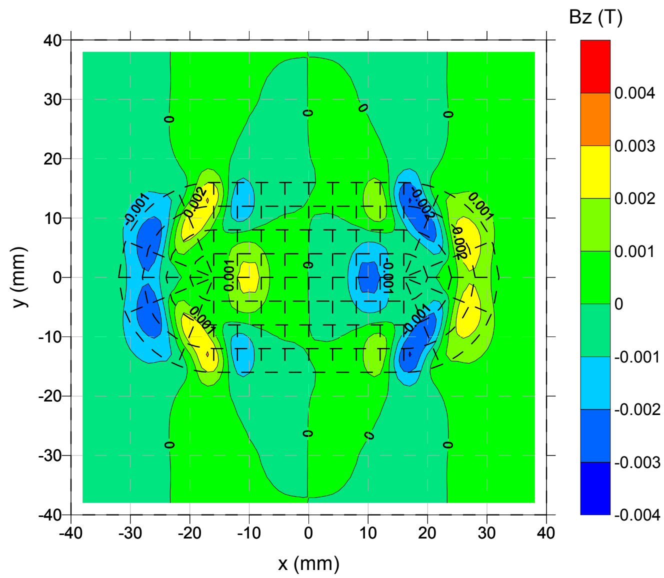

Figure 6 MFL radial component (z direction) stress-only contour plot for the axially elongated dent model shown in Figure 4. Note the scales at the side which indicate that the magnitude of the stress effects is smaller that of the geometry effects. The dotted lines on the figure indicate the dent perimeter and the lines on top of the dent are the individual segments seen in plan view.

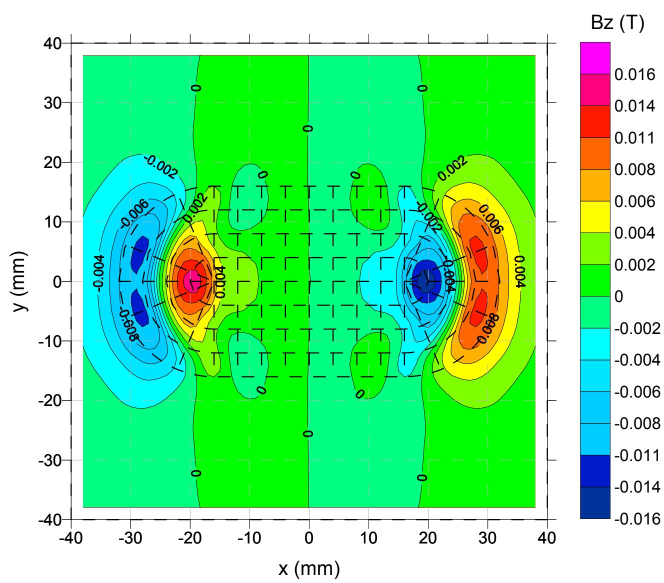

Figure 7: Combined stress+geometry MFL contour plot (radial component) for the 2:1 axially elongated dent, obtained from the magnetic FEA model.

Item No. 8 - Subtask 2.1: Modelling stress pattern around circular dents containing corrosion pits

A stress FEA model was constructed for a circular dent. The corrosion pit was considered to be introduced after the dent was formed, and therefore has little effect on the residual stress pattern. The stress FEA results are shown in Figure 8.

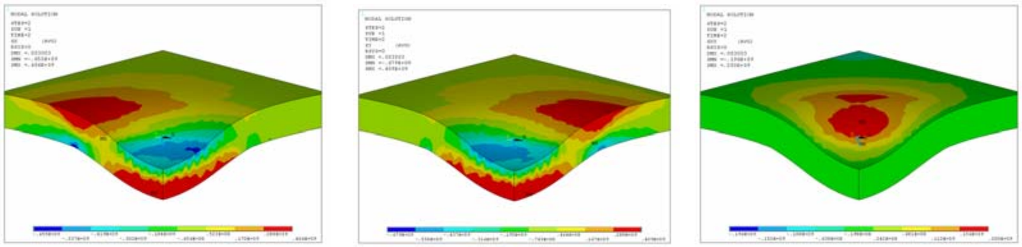

Figure 8: Residual stress patterns for Normal Y (left), Normal X (middle) and shear stresses (right).

Future Activities

Planned activity over the next 90 days will include work on all subtasks related to the third milestone identified in the agreement. These include:

- Modeling of MFL patterns around circumferentially-oriented oval dents.
- Observing experimental MFL patterns around circumferentially-oriented oval dents.
- Continue observing experimental MFL patterns around axially-oriented oval dents (completing the work begun in the 2nd Quarter).
- Model MFL patterns from circular dents with corrosion pits.
- Observe experimental MFL patterns from circular dents with corrosion pits.

Partners in Success

- Electricore, Inc. www.electricore.org
- Pipeline Research Council International, Inc. (PRCI) www.prci.org
- Queen's University www.queensu.ca/homepage/
  www.physics.queensu.ca/~amg/applied_magnetics.html

ELECTRICORE
POWERING THE FUTURE

Principal Investigator

Lynann Clapham

Queen's University

Office: 613-533-6444

Fax: 613-533-6463

lynann@physics.queensu.ca